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REPORT ON RESULTS ACHIEVED WITH SEAS EXPERIMENTAL MILL

J. Juul

Translation of "Beretning om resultater opnået med Seas
    forsogsmølle," Elektroteknikeren, pp. 5-12

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16. Abstract   The SEAS experimental windmill was built in order to attempt operation of a three-phase alternating current generator with a wind turbine as drive power in conjunction with existing AC installations. Testing in natural wind was carried out on the wing shapes that have proved in wind-tunnel tests to be the most feasible. Investigations were made on how much power can be achieved per unit area within the periphery of the wingtips (= wingspread area). Annual production that can be achieved per unit of wingspread area was determined. The following requirements were worked out experimentally: the most favorable wingtip velocity; regulation arrangement of the wing; the necessary automatic apparatus. Finally, the maximum effect of the wind turbine's axle in the wind direction was measured.

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The reason for building the SEAS experimental mill was: /5*

1) to attempt operation of a three-phase alternating current generator with a wind turbine as drive power in conjunction with existing AC installations.

2) to test, in natural wind, the wing shapes which have proved in the wind tunnel to be most feasible for the given objective.

3) to investigate how much power can be achieved per unit area which is within the periphery of the wingtips, which area is called the wingspread area in the following report.

4) to determine the annual production which can be achieved   /6 per unit of wingspread area.

5) to work out experimentally:
    a) the most favorable wingtip velocity;
    b) regulation arrangement of the wing;
    c) the necessary automatic apparatus.

6) to measure the maximum effect of the wind turbine's axle in the wind direction.

Construction of the Experimental Mill

A wingspread of 8 m was chosen. In this choice it was decisive that a larger wind turbine would be more difficult to experiment with and more expensive to build, and since the object of the experiments was to determine the magnitude of the various

*Numbers in the margin indicate pagination in the foreign text.

factors per wingspread area, it was assumed that this size was sufficient for this purpose.

The height of the tower was chosen at 12 m, because the previous wind strength measurements were made at that height.
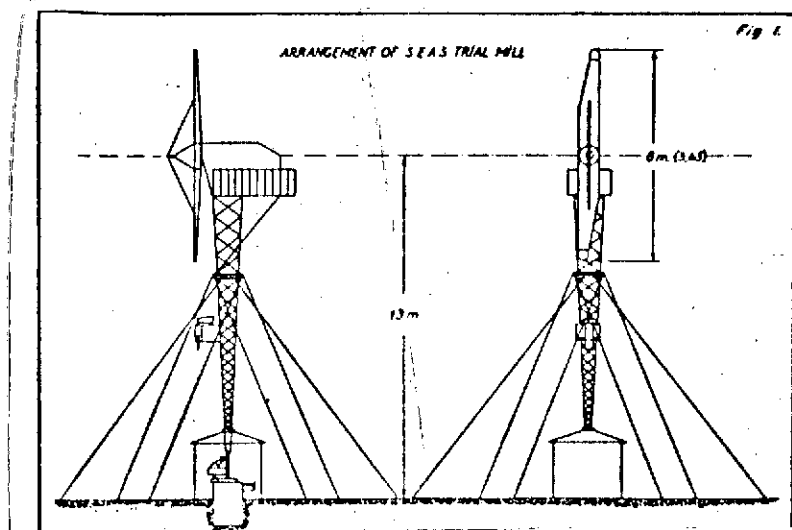

Fig. 1.

The tower is, as shown in Fig. 1, braced with guywires fastened to a ring mounted on the tower at a height of 7.5 m, in which the tower can rotate.

The tower's bottom pivot rests upon an elastic arm, to which is fastened a self-registering pressure gauge, so that the pressure which appears in the bottom socket due to tension in the guywires can be measured. The tension in the guywires will appear partly due to wind pressure on the tower itself and partly due to the pressure which results from the drag of the wind by the mill's path through it.

At the top of the tower there is a housing in which the mill's main axle is mounted. On this there is a chain drive to a counter-shaft, and from this the generator is pulled with the aid of a V-belt. In addition, a braking device is mounted on the main axle.

The lower portion of the tower goes through the roof of a shed set on a concrete foundation, where the bottom socket is located. In addition, on the foundation, with the bottom socket as the center, there is another gear, which is connected through a transmission to a little electric motor, which can be started

in either direction by a wind vane on the tower and thereby keep the mill into the wind.

In the beginning, the experimental mill was equipped with two generators, one of 3 kW with six poles and 1000 rpm, and one of 10 kW with four poles designed for 1500 rpm.

The automatic apparatus was set up in such a way that the little generator was cut in at 5 m/s of wind. At 8.5 m/s, the little generator was switched off and the big 10 kW one cut in. The cut-in and switching occurred with the aid of a wind-pressure switch.

The wings are constructed as shown in Fig. 2 and have a form which was found suitable in wind-tunnel experiments. The outermost part of the wings is shaped like a rotatable flap, whose axle can move approximately 60 mm in its longitudinal direction   /7 with a joint, whereby the flaps can be rotated 90°, so that in flight they can stand upright with the fixed wing surface and perpendicular to it.

The tension in the axle of the flaps occurs by means of a wire through the hollow wings to the main axle, where a system of levers transmits the motion to a tension rod through the mill's main axle, which has a hole bored through it. The tension rod is connected to a plunger in an air pressure cylinder, in such a way that the mill's wings can be set by introducing compressed air into the air pressure cylinder, whereby the mechanical brake is released simultaneously.

The air access to the cylinder is regulated with the help of a regulator valve which is electromagnetically governed in such a way that the valve closes off the cylinder's exhaust aperture at the same time that it opens the air intake when a voltage is applied to the electromagnet.

In normal operation of the AC generator, the mill runs at a fixed rate of revolution without being influenced by varying wind forces.

In case the AC generator is shut off from the existing installation, the current to the regulator valve's electromagnet is shut off immediately. The valve will close for air intake and open for exhaust of air from the cylinder. The end flaps on the wings will turn perpendicular to the wing surface and act as brakes on the wings. At the same time, the mechanical brake on the mill's main axle will start, and the mill will come to a stop.

If there is an interruption in the current from the network, such that part of it remains in connection with the asynchronous generator, it can occur that the mill's generator could be magnetized by capacitive load on the part of the network which remains in connection with the mill's generator. This will then retain voltage on the part of the network which the mill's generator is connected to, insofar as the wind conditions and the load permit. If the load on the network is less than the equivalent output which the mill can produce, the rate of revolution of the latter will increase and the generator voltage will climb above normal. In order to prevent this, there is mounted on the mill's main axle a centrifugal regulator, which releases air from the air pressure cylinder; this prevents the mill from exceeding the normal rate of revolution appreciably.

In the beginning of February 1950, the experimental mill was ready to provide current to a 3 x 380/220 V AC network.

In order to determine the experimental mill's output, both a directly indicating and a self-recording wattmeter as well as a kWh meter are inserted in its circuit. To determine the wind force, a self-recording anemometer was placed 80 m from the

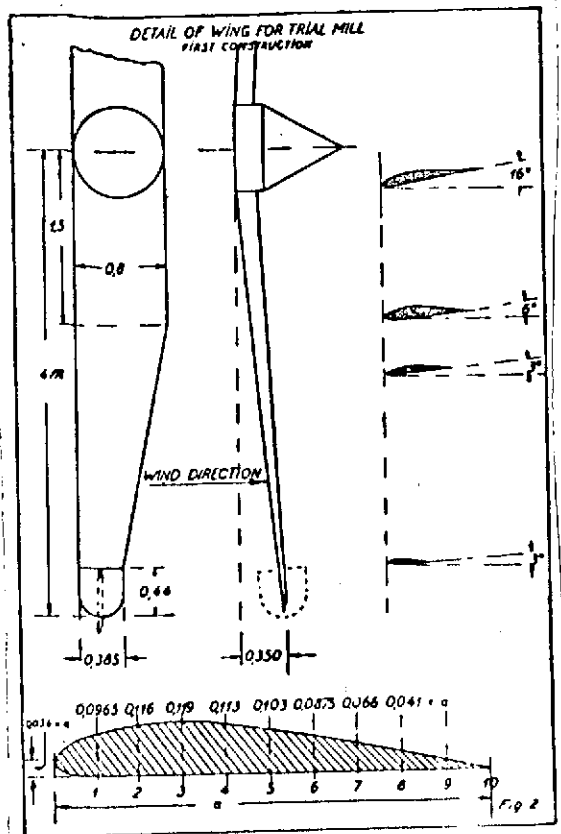DETAIL OF WING FOR TRIAL MILL
FIRST CONSTRUCTION

WIND DIRECTION

Fig. 2.

experimental mill, and a
directly indicating anemometer
was placed right next to the mill.

The mill's instantaneous
power is determined by taking
simultaneous readings from
the directly indicating watt-
meter and the directly indicating
anemometer. Due to eddy currents
in the wind, these readings show
variable conditions. By making
a great number of readings and
noting these in a coordinate
system with the power as the
ordinate and the wind force as
the abscissa, a curve can be
drawn which gives a relatively accurate picture of the magnitude
of the power at various wind forces. The accuracy of the power
curve can be checked by computing the amount of energy by means
of the indicated wind force multiplied by the power curve's
corresponding units and comparing the result with the kWh meter's
reading. This check was made during the months of May, June,
and July, while the mill was in constant operation. The check
showed good agreement between the computed amount of kWh and
the meter reading of produced kWh.

During the power measurements there proved to be no distinct
advantage in using two generators, each with its own wingtip
velocity, rather than only using a single generator of the proper
size. In the first case, construction costs are increased and
automation is complicated. In the second case, a less expensive
installation is obtained with the simplest possible automation.

By changing the generator's pulley, power curves could be made for various wingtip velocities.

It proved to be the case that the best conditions were obtained at a wingtip velocity of 38 m/s.

At a wind velocity of 7 m/s, the efficiency is greatest, i.e., 70% of the total wind power, and from 6 to 10 m/s wind velocity, the average efficiency is around 60%. At a wind velocity above 10 m/s, the efficiency drops so much that a regulation device to reef the mill in strong winds and gales is superfluous. The /8 mill will not be able to overload the generator, due to this condition, no matter how hard the wind blows.

We have found that the wingtip velocity of 38 m/s mentioned is most favorable under the wind conditions prevalent on Zealand. It is possible, however, that it would pay to go up to a somewhat greater wingtip velocity where wind conditions are different, with more frequent strong winds than on Zealand.

Curve 2 in Fig. 3 shows power converted per m^2 of wingspread area. This factor can be used to compute the power for other wingspread areas and to determine the annual obtainable energy under different conditions. For example, the annual energy per m^2 of wingspread area is computed for the measured wind strength at the following locations:

Location	kWh
Dalby Hill, Central Zealand (1949)	376
Island of Enø near shore of Smaaland Sea (1949)	627
Blaavandhuk on west coast of Jutland (1949)	702
Meteorological Institute, Copenhagen (1949)	367

Figure 4 shows the number of hours with various wind velocities for the year 1949 for the localities mentioned above. It will be evident from this that a considerably greater annual power can be
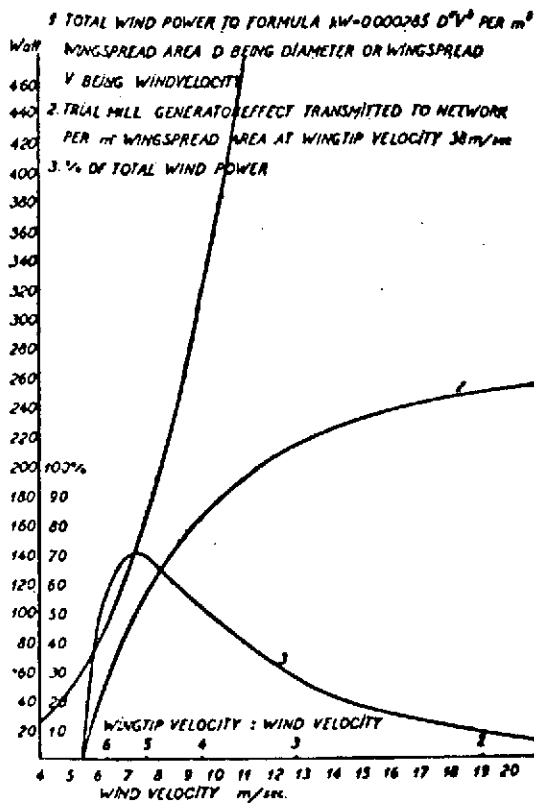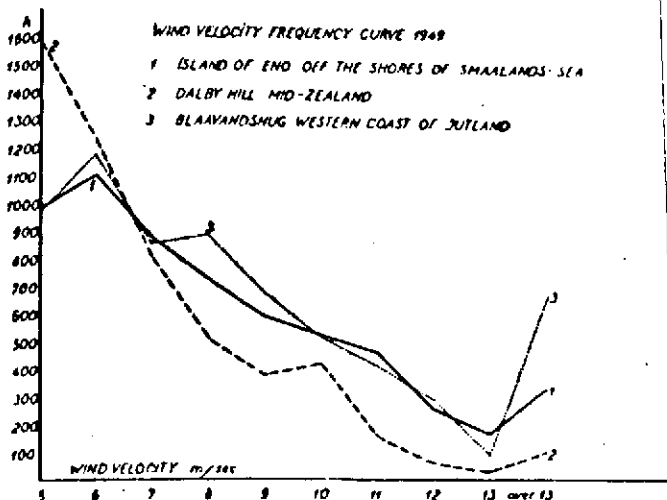
Fig. 3.

Fig. 4.

obtained when the wind turbine is located along the coasts rather than inland, even though the mill is located on a hilltop.

As mentioned under the description of the mill's construction, the wing's power is regulated by the fact that the outermost ends of the wings are designed as brake flaps, which can be rotated by means of their mounting, so that in braking position it assumes an alignment perpendicular to the wing surface. The brake flaps' surface is approximately 4.5% of the area of the wings toward the wind. These brake flaps have proved to be large enough to brake the power of the mill so much that the friction brake mounted on the main axle can stop the mill completely under any conditions. /9

With the transition to operation with only one generator, the original automatic apparatus was exchanged with the automatic apparatus shown in Fig. 5.
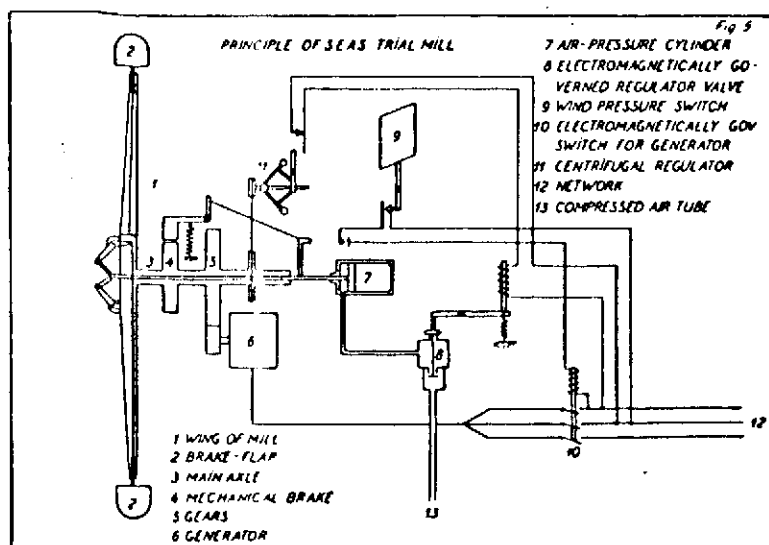
Fig. 5.

The wind pressure plate, which is equipped with an adjustable oil damper, makes contact with an electromagnetically governed switch for the generator at a wind velocity of approximately 5.5 m/s. This starts up like an ordinary asynchronous motor, and when the wings have reached sufficient velocity, the motor works as an asynchronous generator, in that it is now magnetized by the existing AC network, i.e., it withdraws kW from it and furnishes kWh. In case there is no surplus of kS in the network for the magnetization of the generator, it would conceivably be profitable, at wind power stations with asynchronous generators, to install capacitors of the proper size to take over the magnetization of the generator.

In Denmark there are statistics on annual production from wind electrical stations in conjunction with smaller AC stations, which in addition to wind power use diesel engines in conjunction with storage batteries for electrical production. An inspection of the annual electrical production by wind power yielded the following results for the best five stations in the following categories:

Wind turbines of recent construction with three streamlined wings 24 m in diameter, average for the years 1943-1946, per m² wingspread area .... 212 kWh

Equivalent with two wings, 17.5 m in diameter, per m² wingspread area .... 190 kWh

Older construction with flap-sails and four wings, 18 m in diameter, per m² wingspread area ...... 160 kWh

In comparing these figures with those obtained at the experimental mill, it must be taken into account that wind power stations which produce electricity for existing substations must be located in their immediate vicinity, which usually means a bad location with regard to wind conditions. Furthermore, these mills must be equipped with an effective regulation device in order to avoid excessive voltage variations in the stations. This regulation means a cutback of part of the mill's output.

In addition, small electrical stations will not always be able to consume the mill's entire output, and conditions do not always permit accumulation of the portion of the mill's output which cannot be consumed immediately.

When considerably better results are obtained at the experimental mill, it is not only due to a better wing design, but also /10 to a better location, and to the fact that all the energy that the mill can produce can be fed into the AC network without a cutback.

Decisive in the construction of the tower as well as the wings is the effect which these parts are exposed to at maximum wind velocity.

When the wings of the mill go around in the wind, the latter is retarded to a greater or lesser degree depending on the wingtip velocity and the load on the mill. In case the wings are allowed to run without load and as fast as they desire, the wingtip velocity will be approximately 9-10 times the wind velocity. The wingspread area will then offer just as much resistance to the wind as if it were a completely closed surface. In strong wind the wings will not only be subjected to great centrifugal forces, but also to great backward-bending effects, whereby the tower is also subjected to great effects in the wind direction.

These effects are considerably greater than those which occur when the mill is standing still in the same wind.

The axial effects of the experimental mill were measured up to 25 m/s of wind, and here proved to be 1300 kg, corresponding to 26 kg/m^2 of wingspread area.

Since wind velocities of up to 40-45 m/s can occur, however, it must be expected that considerably greater effects can arise, which there will probably be a chance to measure before the experiments are concluded.

These effects will be greatest in the outermost section of the wings. Furthermore, it must be expected that variable effects can arise in the wingspread, because the wind comes in eddy currents to a certain degree, which is why the wind velocity is not homogeneous in the wingspread area. Thus torsion effects and vibrations can rise in the wings which must be taken into account.

The experimental mill's first set of wings was, as shown in Fig. 2, constructed so that they were bent backward in the wind direction. Thereby the centrifugal force in the wings would partially offset the wind pressure on them. The mill was originally designed to run at about 145 rpm, but the experiments proved, as mentioned above, that it was feasible to use only a generator and let the mill run at only 90 rpm.

At this rate of revolution, the centrifugal force in the wings was not sufficient to offset the wind pressure. The result was that after a good 3 months of operation, there was breakage on the wings. The supporting girders in them were telescoping tubes, and the result was that the outermost half broke off.

In the last half of the month of July, the mill had been running in winds up to 25 m/s, and on August 2 the break occurred in a wind of 5-6 m/s. It must therefore have been a matter of a fatigue break, and a calculation with the recorded effect on the mill as a basis also showed that the place of breakage in the 25 m/s wind had been subjected to a load corresponding approximately to the yield point of steel.

With the velocity at which the mill is now designed to run, it appears that the centrifugal force in the wings cannot be of great importance in neutralizing the wind pressure. The new wings are therefore constructed as shown in Fig. 6, in such a way that the pressure on the wings is taken up by stays fastened approximately in the middle of the wings.
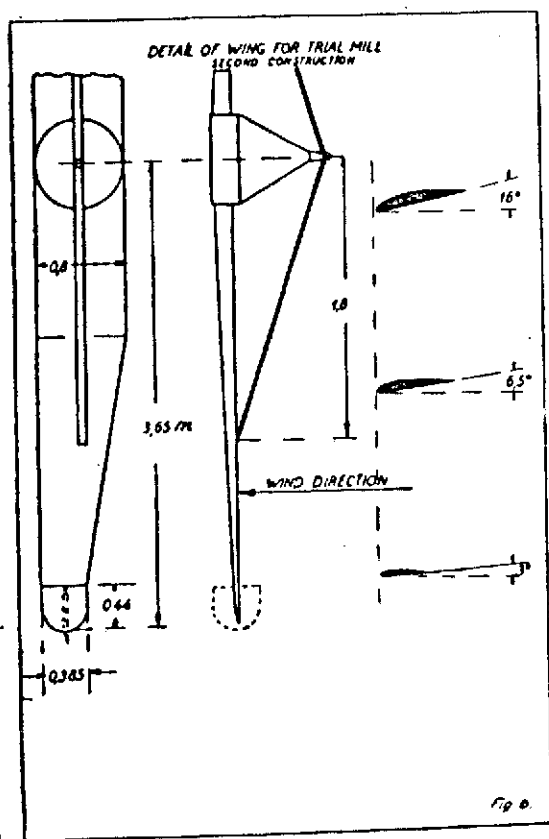
The stays are made of stream-lined flat bars, suitably beveled so that they offer the least possible air resistance.

The experiments discussed above are limited to the operation of a three-phase asynchronous AC generator driven by wind turbine adapted to the system.

Theoretically there is a possibility of expanding the system in large units, but in practice, it would hardly be feasible to build units larger than from 100 to 150 kW, because of the transmission conditions between the mill's main axle and the AC generator.

Fig. 6.

In order to obtain the quantities of energy which are necessary for the system to have practical importance, many units would be required. There is a possibility of mounting these units individually, or of mounting several units on common support towers. In the latter case, it is possible to get some of the units mounted at a greater height than if they were constructed on separate towers. In the latter case, it would hardly be worthwhile to build the towers higher than 25-30 m. If, for instance, four units are mounted on a common rectangular tower, two of the units will be around 50 m high, and this will mean a considerable increase in the amount of energy. The experiments concerning which course of action would be more economical to pursue have not been concluded.

Furthermore, there is also a chance of using other transmission methods between the mill and the generator than the ones mentioned above, and different transmission conditions may possibly also mean different sizes of individual units.

At the moment, it may seem quite laborious to have to build thousands of individual mills, but these would, in that case, be spread over a large area in conjunction with an extensive supply network.

In Denmark a generation ago, there were about 3000 Dutch windmills with a wingspread of from 20-24 m, and there were many more wind engines of smaller sizes on farms and at smaller industrial plants. Construction of equivalent wind power stations of modern design would, however, produce electricity amounting to almost all of Denmark's present electrical consumption.

Construction of wind power stations to the extent necessary requires large investment of capital, and therefore it is of

economic importance for all possibilities to be studied in order
to find the best solution to the question.

In order to compare various types of wind power stations, it
is important to use terms and measurements which can be immediately
compared. It is suggested that this question be discussed and   /12
that the wind power station's capacity be indicated by a table of
the kW output, for example, per m^2 wingspread area at a wind
velocity between 5 and 15 m/s and at an outside air temperature
of 15°C and an air pressure of 1000 millibars.